CLEAR COAST
CONSULTING, INC.

TECHNICAL MEMORANDUM

Date: **August 23, 2020**

To: **Alaska Department of Environmental Conservation, Division of Water**

From: **André Sobolewski, Clear Coast Consulting, Inc**

Subject: **Review of water treatment plants proposed in FEIS for Pebble Project**

I was retained by Earthworks to review documents relating to water treatment in the Final Environmental Impact Statement (FEIS) for the proposed Pebble Project. I reviewed the FEIS and its appendices, building on previous reviews of the water treatment system proposed in the Draft and Pre-Final Environmental Impact Statement (PFEIS), including several Requests for Information (RFI021a-k) released after the PFEIS was issued.

1 Key Findings

Given the sensitivity of the receiving environment, the water treatment scheme proposed in the FEIS is unacceptably risky. It will fail to meet applicable water quality criteria for a number of contaminants, including selenium, to which productive ecosystems downstream from the proposed Pebble Mine are especially sensitive.

The proposed water treatment plants (WTPs) are large, complex and, contrary to the United States Army Corps of Engineers' (USACoE) assertion, do not use industry standards and proven processes and technologies. On the contrary, the chemical process proposed for selenium removal is unproven, will be ineffective and result in exceedances of Alaska Department of Environmental Conservation (ADEC) water quality standards during mine operation. The treatment performance predicted for other contaminant is overly optimistic: there is no reasonable assurance that WTPs will discharge effluents that meet State standards. Worse, their claimed performance is not supported by testwork, published literature or case studies. Any treatment system presented in an FEIS without substantiation cannot be credible, especially one that uses unproven technology.

Several risks associated with the proposed treatment systems have been identified, including the very high risk of non-compliance for selenium, a high risk of producing non-compliant effluents due to a build up of salts in the Main Water Management Pond, and the risk that this problem cannot be remedied for technical or economic reasons. Most worrisome is the risk that the company will default on its obligation to treat water in perpetuity.

In conclusion, the water treatment systems presented in the FEIS are complex, unproven and are predicted to discharge non-compliant water that will impact sensitive ecosystems downstream from the proposed mine. The treatment scheme proposed in the FEIS should be rejected.

2 Qualifications and Professional Expertise

I am an environmental consultant with a PhD in Biology and 30 years of professional experience (résumé appended). I have participated in nearly twenty Environmental Impact Assessments and have developed a guidance document for assessing impacts of planned mines for the Yukon government (through the Yukon Environmental and Socio-economic Board, YESAB). I have participated in nearly 100 mining-related projects, principally in the development or evaluation of water treatment systems. Most of my work involved the evaluation and/or design of water treatment systems at mining operations. For example, I participated in the evaluation of requirements to upgrade the water treatment systems at the Yanacocha mining complex, which include two reverse osmosis plants, a project comparable in scope and scale to the Pebble Project. My clients include natural resources industry, government, First Nations and non-government organizations. I have also provided expert technical opinions in legal cases. This background qualifies me to provide an unbiased expert technical opinion on the proposed water treatment plants for the Pebble Project.

3 Treatment System Design

The USACoE description of the water treatment plants (WTPs) proposed for this project (FEIS Appendix N – Project Description) is well-presented, but I am disturbed by several aspects of this treatment system design.

USACoE states in the FEIS Appendix N – Project Description:

> *WTP #2 will treat water from the main WMP with treatment plant processes commonly used in the mining industry around the world.*

I will argue below that this is not true for the process for selenium removal. However, there is a broader objection to this statement: the need for this particular design is never rationalized, save for the process for sulfate removal. None of the other processes are identified as being appropriate to remove the contaminants identified in Appendix K - Section 4.18. Water and Sediment Quality. Within the FEIS, there is not a single statement explaining how the treatment system will remove individual analytes to an acceptable level, such as:

> *The concentration of contaminant x will be decreased to xxx mg/L, which is below the Alaska Department of Environmental Conservation (ADEC) criteria. This prediction is supported by [testwork, case study, industry standard].*

This makes it nearly impossible to evaluate "fitness-for-purpose" of any component of the treatment system specified by the USACoE, and to assess the validity of their assertions. It is inappropriate to state that further testwork during the permitting process will demonstrate the effectiveness of the proposed treatment systems. Their effectiveness in meeting state criteria must be demonstrated in the FEIS, and before the state can certify the project will meet criteria.

This problem is apparent in the grievously flawed statement by USACoE in the Chapter 5.0 – Mitigation, Table 5-2:

> *Additional modeling and pilot plant testing <u>would further evaluate the feasibility of WTP processes</u>, assess maintenance requirements, reduce uncertainties, and refine discharge water quality predictions.*

NO! There can be no doubts that treatment is feasible. If there is any doubt, then the doubtful process or technology must be discarded in favor of one that is known to be feasible. This is what is understood by adopting Best Management Practices and Industry Standards. The Pebble Project is not a place to experiment: there's too much risk at stake. Any technology presented in the FEIS must be established and should not be in doubt.

In my own assessment, I find that there are questionable choices in the design of the proposed treatment system. For example, the first step in the common treatment process – the addition of permanganate for metal oxidation, followed by their precipitation with ferric chloride – is the correct process for removing arsenic, but it is the opposite of the process for removing selenium. In the latter case, a <u>reductant</u> is required (such as zinc dust), not an <u>oxidant</u> like permanganate. In fact, oxidation *will prevent* the follow up reaction that removes selenium. In this process, arsenic will be removed but not selenium, contrary to the claim in the FEIS.

In all my previous assignments to conduct or review Impact Assessments, including work in Canada, USA, Panama, Peru and Armenia, I have never seen a treatment system being presented without justification of its ability to meet mandated effluent quality. Typically, an EIS presents a table of analytes in mine water, denotes predicted exceedances, proposes treatment processes to decrease their concentrations and demonstrates their suitability in removing contaminants below mandated discharge concentrations. The complete absence of such justification for the treatment system proposed by the USACoE is unacceptable. Specifically, the assertion of "*processes commonly used in the mining industry*" cannot be tested because it is not justified in relation to the treatment of specific contaminants.

In the absence of any analysis of the suitability of the proposed treatment system to meet ADEC criteria, I conducted my own. For this assessment, I relied on data provided in: Predicted Water Quality Inflows for WTPs in Operations and various phases of Closure. An independent analysis of that document (Wlostowski, 2020) cast doubt on some of the predicted inflow concentrations for certain analytes, but these uncertainties were merely noted, not accounted for. As with any design work, the 90th percentile concentrations were used to evaluate the suitability of the proposed treatment process.

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For this analysis, I used the proposed WTP #2 for mine operations (Figure 1), as it is among the most comprehensive WTP proposed for this project (WTP #3 also comprises an evaporator/crystallizer unit). This treatment system shares many components with WTP #1 and WTP #3 and any analysis of WTP #2 will readily apply to these other treatment plants.

Analytes in WTP #2 influent requiring treatment are presented in Table 1. They are taken from Table K4.18-5-11, which notes contaminants predicted to exceed ADEC criteria during mine operations. These analytes are similar, with some variation, to those found in inflows to the other two project WTPs during operations and closure.

Table 1. Analytes that exceed water quality criteria.

Analyte	90th Percentile concentration mg/L
Sulfate	1,747
Antimony	0.0645
Arsenic	0.0869
Beryllium	0.0372
Boron	0.754
Cadmium	0.0179
Cobalt	0.0515
Copper	0.0100
Lead	0.0372
Manganese	1.85
Mercury	0.000262
Molybdenum	3.65
Nickel	0.115
Selenium	0.0397
Silver	0.0031
Zinc	2.61

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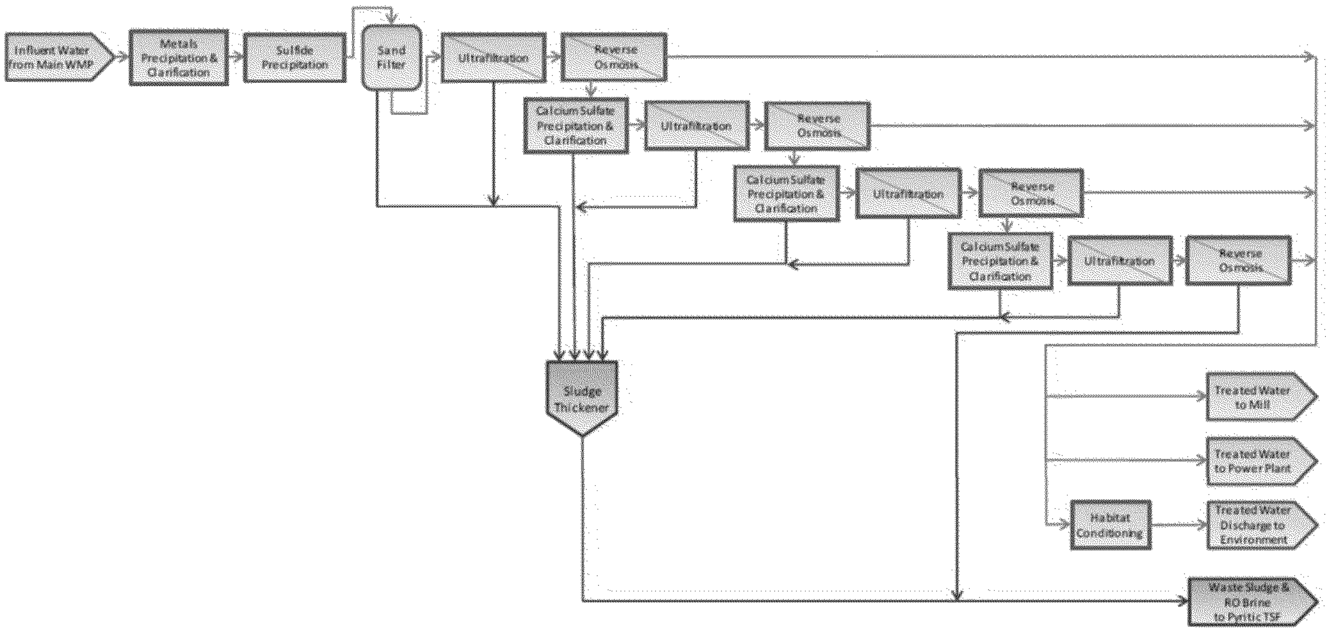

Figure 1. Water Treatment Plant #2 - Operations Phase. Taken from USACoE FEIS Appendix N – Project Description

The first step in the treatment process – permanganate oxidation and ferrihydrite precipitation – is effective in removing arsenic and manganese and is widely used. Depending on treatment conditions (pH, ORP), molybdenum will also be removed to acceptable levels, as demonstrated in the treatment plants at the closed Brenda Mine (Aubé and Stroiazzo, 2000) and at Coldelco's El Teniente Mine (Aubé and Vergara, 2010).

The oxidative precipitation of manganese into an insoluble dioxide (pyrolusite) will also remove trace metals, including cadmium, cobalt, copper, lead and zinc. This may be beneficial to overall treatment, but the starting concentrations of manganese are relatively low and it is difficult to predict by how much trace metal concentrations will decrease.

A contractor for the Pebble Limited Partnership (PLP) reported that permanganate oxidation, followed by ferrihydrite precipitation will remove selenium (RFI 021e Addendum, 2019), but this process is wrong. Ferrihydrite will precipitate the *partially-reduced* selenite (SeO_3^{2-}), not the *full oxidized* selenate (SeO_4^{2-}). Thus, an initial oxidative step is inappropriate because a chemical reduction of unreactive selenate to selenite is required, such as by addition of zinc dust (Alberta Environment, 2005). The subsequent ferrihydrite precipitation will decrease inflow concentrations of selenium to ~0.020 mg/L. An additional step is necessary to decrease its concentration < 0.005 mg/L.

Iron co-precipitation can remove several metals; however, their concentrations will not be decreased low enough to meet stringent water quality criteria (MEND, 2014). A High-Density Sludge (HDS) system is required to decrease metals to trace levels, but this is not what is proposed at Pebble. Therefore, additional treatment will be required to decrease the concentration of most metals to levels acceptable for discharge.

Several metals form highly insoluble sulfides and nominally will be removed to below ADEC criteria in the sulfide precipitation stage. These include antimony, cadmium, cobalt, copper, lead, mercury, nickel, silver and zinc. Sulfide precipitation is expected to be highly effective, but some uncertainties remain regarding the ability of this process to produce fully compliant effluents. For instance, it is well known that metals like zinc can form colloidal sulfides that remain in solution (Gammons et al., 2000; Jarvis et al., 2015). Potentially, these colloids will be retained in the membrane filtration units, either in sludge of the UF unit or in retentate (or reject) in the reverse osmosis units. Either way, it is probable that colloidal zinc sulfides will be returned to the Pyritic TSF, where they will re-dissolve and return to the water circuit, resulting in gradually increasing concentrations. This potential problem cannot be resolved without testwork on actual mine water, nor is it easily resolved after it is detected during mine operation.

Mercury removal can nominally occur during the sulfide precipitation step, but it is difficult to decrease its concentrations to exceedingly stringent water quality standards unless specialty chemicals are used. The conditions for its effective removal must be determined through testwork, although this usually involves considerable R&D (Blythe and Owens, 2008), but such a process can easily be bolted on after the sulfide precipitation step.

Selenium is proposed to be removed as a selenide via precipitation with sulfide. This reaction is technically possible, but it requires conditions that are not met in a mining environment (low redox potential, high sulfide concentrations, etc). To my knowledge, this process has never been used in a commercial application, and certainly never at a large-scale mining operation. Several specialists who know or investigated this process[1] have confirmed that sulfide precipitation is impractical and has never been used for selenium removal from mine water.

PLP (via HDR, 2019) acknowledged that selenium is a key contaminant[2], thus requiring special attention. In the Draft Environmental Impact Statement (DEIS), a biological treatment process was proposed for selenium removal. This is widely recognized as the current state-of-the-art and established industry practice (Alberta Environment 2005; MEND, 2014; NAMC 2010, 2013, 2020). Its rejection in the FEIS in favour of the unproven and untested sulfide precipitation process is unjustified, a retrenchment from established norms and industry practices. **The process for selenium removal proposed in the FEIS goes against current practice and is not supported by any published experimental design or case study.** The literature presented in RFI 021h to support their process is outdated and has been superseded by the more recent publications cited above. Moreover, an extensive review and testing of selenium treatment technologies by Teck Coal concluded that sulfide precipitation is not a viable process[3] and that biological treatment is the only process that produces compliant effluents at their operations (Teck 2014). **Thus, the assertion by the USACoE that "*WTP #2 will treat water from the main WMP with treatment plant processes commonly used in the mining industry around the world*" is false with respect to selenium**.

In the absence of chemical precipitation, selenium will be removed in the WTP by membrane filtration, either via nanofiltration or reverse osmosis. Given that selenium-containing brine generated by membrane filtration will be discharged into the Pyritic TSF, there is a concern that its concentration will build up in mine water because WTP #2 → Brine → Pyritic TSF → Main WMP → WTP #2 is a closed-loop circuit. This concern was acknowledged by Pebble and was analyzed through a water balance and water chemistry model (Knight Piésold, 2019). I reviewed this model.

The KP model assumes incorrectly that all the incoming selenium will be removed by chemical precipitation: its predicted concentrations in brine was 0.006 mg/L (HDR 2019, Table 3, as indicated in

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[1] Dr. Dirk Wallschläger, School of the Environment/Chemistry, Trent University, Canada; dr.ir. J (Jan) Weijma, Environmental Technology Group, Wageningen University and Research; Drs Stephane Brienne, Section Leader, Environmental Technology, and Alberto Gonzalez, Principal Metallurgist, Applied Research and Technology, Teck Resources Limited.

[2] "The water balance and water quality analysis of the loading and behavior of salt and key parameters of concern, such as selenium …" (HDR, 2019).

[3] Drs Stephane Brienne and Alberto Gonzalez, Teck Resources Limited. Personal Communication.

Knight Piésold 2019, Table D3.1). I have already argued that chemical precipitation will not work, but we know that selenium will be removed via membrane filtration in WTP #1 and #2. I assumed a 90% removal rate, as previously demonstrated (Zamzow et al, 2019). I also estimated that an additional 5% of selenium in brine will be removed via co-precipitation with gypsum in the sulfate removal stage[4].

From these removal rates, I calculated that selenium concentrations in brine will be **2.04** and **2.96** mg/L in WTP #1 and WTP #2, and that its concentrations in the Pyritic TSF inflow will be **1.94** and **2.81** mg/L, respectively[5]. Using these concentrations, I developed a simplified water balance model (a simplified version of the KP model) with KP's inputs for flows and chemistry, but substituting my calculated brine selenium concentrations as inputs. My model assumes that selenium concentrations in brine will remain constant regardless of its influent concentration: this is an acceptable simplification because the more accurate value (which is difficult to determine) will only increase the influent concentration marginally. Additionally, the calculation does not correct for increasing salt concentrations in the WTP #2 inflow, which are expected to increase and to impair selenium removal rates. Thus, the resulting calculations are conservative. **These calculations predict that selenium concentrations in the Pyritic TSF and in the Main WMP will gradually build up, increasing by a factor of ten in the Main WMP by Year 6**. The model cannot be used to determine selenium increases past that time because additional interactions add uncertainty to expected removal rates.

The above finding flatly contradicts the assertion by Pebble that selenium concentrations will not build up in this closed water management circuit. Not only will selenium concentrations increase, they will reach levels that overload the capacity of WTP #2 to meet the state discharge criteria for selenium. **As currently designed, WTP #2 effluent will exceed the Alaska state limit of 0.005 mg/L for selenium within 6 years of operation**. Given the sensitivity of wetlands downstream from the mine, it is almost certain to impact them. This grave consequence is the result of substituting the biological treatment process proposed in the DEIS for the chemical precipitation process proposed in the FEIS.

Boron and Beryllium will be removed via reverse osmosis (RO). The latter can also be removed by ion-exchange, but this process is unlikely to be as practical or economically-viable as RO.

Sulfate may be removed effectively by the combination of membrane filtration and calcium precipitation. Reviews of treatment technologies for sulfate removal considered membrane filtration among the most promising technologies (INAP 2003, Boswell 2004). However, the treatment process proposed at Pebble has only been implemented *once* at full-scale (Hutton et al., 2009), so it cannot be considered a proven technology or an Industry Standard. Moreover, the existing treatment plant using this process only became operational after considerable research and development work by Anglo American and this is likely to also be the case at Pebble. The process has potential, but still requires more development (Aubé and Lee, 2015), and can only be considered a technology at an advanced stage of development.

[4] This removal rate was observed by Dr. Stephen Day, SRK Consultants. Personal Communication.

[5] The difference is accounted by a 5% loss in the sulfate precipitation step.

Depending on the resources devoted to this, it may take 3-4 years before this process can be operated at full-scale at the Pebble Mine, adding uncertainty about the ability to produce a compliant effluent for sulfate.

4 Treatment performance

At the Pebble Mine, the importance and sensitivity of the downstream ecosystems give very little tolerance for exceedances in regulated contaminants. If the performance from the treatment plants is not as effective as predicted, there is a strong likelihood of impacts. For this reason, I examined closely the performance predicted for the proposed treatment systems and evaluated the predicted removal rates against performances from known, operating treatment systems.

The fact that the USACoE proposes an unproven technology for selenium removal begs the question: how did they determine selenium effluent concentrations in Appendix K - Section 4.18. Water and Sediment Quality? **How did they determine effluent concentrations for selenium, given that there is no commercial treatment plant relying on the chemical process they propose?**

If the predicted selenium concentrations in treated effluent are not validated by any testwork, case study or scientific report, that raises similar questions about the predicted effluent concentrations for other constituents, which are similarly unsubstantiated by testwork, case studies or scientific reports. The effluent concentrations for a number of key analytes are exceedingly low and imply extraordinarily high removal rates, as shown in Table 2 below.

The removal rates in Table 2 are not substantiated in the FEIS by any testwork, literature or case studies. Metal concentrations in WTP effluents are exceedingly low and appear to be predictions from modelling simulations rather than real-world experience. Given the well-known fact that metal removal becomes very difficult at trace levels, these removal rates appear abnormally high and are not credible. These predictions are even less credible when accounting for the impairment of removal efficiencies by salts – it is well-known that removal efficiencies are strongly affected by the salt composition of wastewater (e.g., Peng and Escobar, 2003) – and because salts are predicted to build up within the water management circuit. There is no indication that the removal efficiencies presented in Table 2 account for anticipated increases in salt concentrations. For all these reasons, they cannot be considered reliable.

Table 2. Predicted effluent concentrations and removal efficiencies for WTP#2 during mine operation.

Analyte	Influent concentration (mg/L)	Effluent concentration (mg/L)	Percent removal
Cadmium	0.01879	0.0000021	99.99%
Cobalt	0.054	0.00000236	99.99%
Copper	0.01	0.00000015	99.99%
Manganese	1.85	0.00075	99.96%

Mercury	0.000279	0.0000000007	99.9997%
Molybdenum	3.90	0.0017	99.96%
Selenium	0.041	0.000537	98.7%
Sulfate	1765	71.7	95.94%
Zinc	2.74	0.00002	99.99%

I compared the predicted removal rates at Pebble with those for reverse osmosis systems at other mine sites. A few operations have published removal efficiencies that are relevant to the present case. For instance, the reverse osmosis plant at the Canonsburg, Pennsylvania Uranium Mill Tailings Remedial Action Program (UMTRA) Site (MEND 2008) removes contaminants to low concentrations, but never with the removal efficiencies predicted at Pebble (Table 3). These data suggest that it is difficult to decrease metal concentrations significantly below 0.001 mg/L.

Table 3. Influent and effluent concentrations and removal efficiencies Canonsburg, UMTRA site.

Analyte	Influent concentration (mg/L)	Effluent concentration (mg/L)	Percent removal
Cadmium	0.076	0.01	8.68%
Copper	2.00	0.03	98.5 %
Iron	14.80	0.04	99.73
Manganese	1.61	0.02	99.76%
Radium	1.00	0.6	40%
Uranium	6.40	0.001	99.98%
Zinc	0.16	0.008	95%

Similar to the proposed Pebble WTPs, the eMalahleni water treatment plant uses a triple-pass reverse osmosis configuration (Hutton et al., 2009). It comes close to the same removal efficiencies as those proposed for Pebble (Table 4), but the high removal efficiencies at eMalahleni reflect much higher influent concentrations. Effluent concentrations for metals at either the Canonsburg or the eMalahleni plant do not come close to the trace levels predicted at Pebble.

There are other published reports that provide removal efficiencies for reverse osmosis (e.g., MEND 2014), but they do not provide all the necessary information, including influent analyte concentrations, to allow a valid comparison.

Table 4. Typical influent and effluent concentrations for analytes at the eMalahleni water treatment plant.

Analyte	Influent concentration (mg/L)	Effluent concentration (mg/L)	Percent removal
Aluminum	40	<0.15	99.63%
Iron	210	<0.01	99.99%
Manganese	35	<0.05	99.86%

Sulphate	3090	<200	93.53%

These examples show that metals can be removed effectively by reverse osmosis, but that it seems difficult to decrease their concentrations significantly below 0.001 mg/L. Other factors, like water temperatures, the presence of other cations or anti-scalants, compound this difficulty. **The predictions of metal removal to trace levels by the USACoE cannot be accepted without substantiation, especially considering the unsustainable claims they made regarding selenium removal. Such claims are only acceptable if supported by laboratory testwork, published literature or case studies for every contaminant.** Otherwise, the USACoE is asking us to accept their claims on faith, which is unacceptable.

5 Cation Accumulation in the Water Management Closed Circuit

I have already identified a problem with the accumulation of selenium in the water management closed circuit. There are other problems associated with this approach. Excess calcium and sulfate will be removed from mine water through RO, *but the performance of filtration membranes depends on the concentrations of other cations, such as sodium, potassium or magnesium*. Their concentrations increase markedly in brine and will increase in the water management circuit (WTP #2 Brine → Pyritic TSF → Main WMP → WTP #2 Brine) throughout the operation of the mine, along with calcium and sulfate (Knight Piésold, 2019). This will result in problems of scale formation in the mineral processing plant as well as the water treatment plant. Eventually, the performance of the RO units will degrade beyond the limits of the system because they were not designed for this type of water. Pumps will fail because the pressure on membranes will be too high, or membranes will experience breakthrough.

It is difficult to predict when exactly this breakpoint will occur, but it will certainly occur within the life of the mine. The problem of accumulating salts was previously raised in the DEIS and PFEIS and Pebble's response essentially says: *we will look at the problem when it happens*. This is naïve, unsatisfactory and cannot be disguised as Adaptive Management. This problem may require an expensive solution or, at worse, may be technically unsolvable. Alternatively, there may be a technical solution, but the impairment in reverse osmosis performance may only become apparent after a substantial salt build up in the Main WMP, resulting in a very large volume of briny water to be treated before removal efficiencies can be restored. Potentially, this could lead to a prolonged period of non-compliant operation.

6 Risk Assessment

Any complex treatment system planned by a mining company will undergo an internal risk assessment because it is critical to the operation (i.e., enable compliance with state laws). This is especially critical at the Pebble Project because of the sensitivity of the receiving environment and the potential risk to a world class fishery. Some of the key risks to consider with the proposed treatment system proposed in the FEIS are highlighted below. These include:

- System complexity and scale
- Removal efficiencies/RO effectiveness at increasing salt concentrations
- Unconventional process for selenium removal
- Unconventional process for sulfate removal
- Resources for Research & Development
- Reliability and costs of treatment in perpetuity

6.1 System Complexity

The three treatment systems proposed in the FEIS are complex and very large, which makes them inherently risky. Different contaminants may require very different conditions for removal (i.e., pH/ORP during oxidation/iron precipitation), which will require additional new treatment steps. It is well-known that complex systems are inherently riskier than simple systems, increasing the risk of under-performance or failure.

To some extent, the FEIS acknowledges this risk by building redundant treatment units in the plant designs. However, there is a great risk that a large and complex treatment system will not perform as predicted when there has been no testwork or precedents (case studies) to support the design. Instead, the FEIS appears to rely on vendor literature, which is almost always excessively optimistic. Unexpected problems, such as problems caused by cold water temperature or increasing salt concentrations in the water circuit, may lead to decreased performance and release of non-compliant water. In such a case, a correction would be very difficult and expensive because the problem of salt accumulation is built into the mine plan and system design.

There is an additional risk arising from the assumption of linear scaling with the proposed treatment system. It is assumed that individual components of treatment systems known to be effective at 10 cfs can be scaled up directly to 25 cfs and integrated into a complex treatment system. This is an untested assumption that would normally be resolved through a rigorous test program. This was one of the issues with the eMalahleni water treatment plant that took three years to resolve (Hutton et al., 2009). The same experience has been reported for other, novel large-scale water treatment plants[6].

While some of the risk is inherent to a large, complex treatment system, Pebble could reduce the risk in predicted system performance by using published literature and providing performance data from case studies of comparable treatment systems. This information would provide some assurance that their claims are justifiable. Presently, the FEIS does not provide such assurances. Of course, nothing

[6] Alan Prouty, Vice President, Environmental & Regulatory Affairs, JR Simplot. Personal communication.

compares with testwork conducted with real mine water, and it is disappointing the Pebble has been unable to do so after many years of working on this property.

6.2 Removal effectiveness of reverse osmosis at increasing salt concentrations

The performance of filtration membranes in a nanofiltration or reverse osmosis system is affected by ambient water temperature and salt concentrations. Almost always, their performance must be optimized through a pilot test program for a given mine water. However, the closed water circuit at Pebble (WTP #2 Brine → Pyritic TSF → Main WMP → WTP #2 Brine) adds new complexity and unpredictability to this issue because salt concentrations will be constantly increasing during mine operations. This greatly increases the risk that WTP #2 will fail to achieve the predicted removal rates and produce effluents that are out of compliance during mine operations. This may be very problematic because there will be no quick and easy solutions to resolve this due to the large volume of salty water accumulated in the Main WMP. It may be possible to remedy this problem by adding an evaporator/crystallizer unit to the WTPs, but this will be both very expensive and it may take a long time to process the large volume of water in the Main WMP. This problem is likely to be discovered after several years of operation and the interruption may last 1-2 years, during which time WTP #2 may produce non-compliant effluent (or mining operations may be stopped).

6.3 Unconventional process for selenium removal

As indicated in Section 3, the treatment process proposed for selenium removal is unconventional. Although the chemistry for the chemical reduction of selenate/selenite to insoluble selenide via bisulfide has been demonstrated in the laboratory, those who have investigated this process have rejected it as a viable process for treatment of mine water.

Pebble's proposal to develop this process runs counter to this experience. They rejected the conventional process for biological selenium treatment and assert that they can develop by unproven process without providing any proof. There is no assurance that they will succeed in developing such a process and their proposal should be viewed with great skepticism.

6.4 Unconventional process for sulfate removal

The need for removing sulfate from mine water is a relatively recent development in the mining industry. Dilution has typically been used to manage this contaminant but there is limited opportunity to use dilution at Pebble, resulting in a need to treat for sulfate. Despite the existence of a number of processes for removing sulfate, only two processes have been used at mine sites: membrane filtrations and lime/calcium precipitation of concentrated sulfate. There's only one implementation of the process proposed by Pebble at an operating mine (Hutton et al., 2009).

It took 15 years to develop this under more favourable conditions in South Africa[7]. There is a great risk that Pebble will not succeed in developing the process they propose for sulfate removal, that their removal rates will be less than predicted or that the development process will take much too long or cost too much, resulting in the discharge of non-compliant effluent. Given the long lead-time for developing the process at the eMalahleni water treatment plant, there is a significant risk that Pebble will be out of compliance for a prolonged period during its operations. My own estimate is that developing this process to full-scale may take 3-4 years at Pebble, which runs the risk that the process will not be ready when it is needed.

6.5 Resources for Research & Development (R&D)

Most unconventional treatment systems take many years to develop and require significant investment in R&D. This was the case for the eMalahleni water treatment plant (Anglo American), the reverse osmosis/HDS plants at Yanacocha (Newmont), and the biological treatment plants for selenium at Smoky Canyon (J.R. Simplot) and West Line Creek and Fording River coal mines (Teck Coal). While these large mining companies enjoy steady cash flow from their operations, Northern Dynasty is not in that position: it will require all its cash to acquire mining equipment and build the mine site. They will be hard-pressed to free up the needed resources towards this necessary R&D.

This is not just a problem of money. Most of the above mining companies have their own research facilities (e.g., Teck's Applied Research and Technology Center) with specialized equipment, scientists and technical staff. Northern Dynasty has none of these, in addition to lacking the capitalization necessary to support such development work. This casts doubt on their ability to conduct the R&D necessary to develop their proposed water treatment systems. **Northern Dynasty's claims are very optimistic but they are not in a position to deliver.**

6.6 Reliability and costs of treatment in perpetuity

The ideal of closing out a mine and walking away is never attained. Typically, closed mines continue to discharge contaminated water for a long time and require treatment, often in perpetuity. Conventional treatment systems, like the High-Density Sludge (HDS) process are easy to design, operate and maintain for the long-term, but we have no experience with the long-term operation of large, complex systems such as the systems proposed in the FEIS. Their long-term performance in such a remote region of the world is highly uncertain, which presents a significant risk of failure.

Compounding this uncertainty is the significant problem of paying for the operation and maintenance of such a treatment system for 200-10,000 years. This cost will easily exceed $1 billion and could run in

[7] The colder ambient water temperatures in Alaska carry a higher risk of undesirable side-reactions, such as the precipitation of reactants on the walls of reactors, which will impair their performance.

excess of $3-4 billion. There is a high risk that the Northern Dynasty will not be able to meet its long-term obligations and default, leaving the people of Alaska to bear this burden[8].

7 Improvements to Treatment Plant Designs

In addition to identifying problems with Pebble's proposed water treatment plan, I considered what additional steps would be necessary to provide assurance that the WTP effluents would comply with ADEC standards. The following list is not intended to be comprehensive, but rather to illustrate reasonable approaches that PLP could have pursued. Adopting these additional steps would provide regulatory agencies with a much greater assurance that the proposed WTPs would produce effluents compliant with ADEC standards and would not impact downstream ecosystems.

Any treatment plant operated at the Pebble Mine will be large and complex due to the size of the operation, nature of water to be treated and the sensitivity of the environment downstream from the mine. This inevitably entails risks, as I have discussed above. These risks can best be minimized by using proven technology and demonstrating its applicability at the proposed mine by conducting testwork or by justifying it with published reports of comparable systems operating under similar conditions. This would be the first step in improving the designs proposed at Pebble.

Several other aspects of the proposed treatment plant design should be improved. The selenium removal process proposed in the FEIS is unproven and should be abandoned. Instead, selenium removal could be achieved by combining two processes. First, its initial concentrations should be decreased from 0.03-0.04 mg/L to 0.015-0.020 mg/L through ferrihydrite precipitation (after an initial chemical reduction to convert selenate to selenite). This should be followed by a biological treatment process, such as through a fluidized-bed reactor, to decrease its concentrations to 0.0010-0.0020 mg/L. These concentrations meet ADEC standards and would not impact downstream ecosystems.

Sulfate removal is difficult. It is possible that the 3x/4x pass RO system presented in the FEIS is the most cost-effective option. However, the reject stream from the membrane filtration step should be sent to an evaporator/crystallizer unit *for all the WTPs*, not just WTP #3 during Phase 1 of closure. This will eliminate the problem of salt build up in the water management circuit and prevent deterioration of treatment performance. My estimate is that developing this process would take 2-5 years, which would be taxing for the anticipated mine plan schedule. There is a significant cost consequence to the development and operation of this treatment process: the State of Alaska needs to determine if the project economics remain viable with such a design to avoid the risk of company default.

Testwork is absolutely necessary to validate the proposed WTPs. One important test would be to determine the extent of trace metal removal in the manganese precipitation step via permanganate

[8] As essentially happened at the Faro Mine, in the Yukon.

oxidation. It may be possible that this step would decrease the concentrations of several metals sufficiently that they do not require additional treatment, and this might affect the process flow sheet. Additional testwork is necessary to determine the extent of metal removal in the sulfide precipitation stage and ascertain if their final concentrations meet ADEC water quality standards. If not, additional steps would be required or an alternative process would need to be used.

Mercury is one of the most difficult contaminants to remove. A special step in the flow sheet may need to be added specifically for its removal. Again, this cannot be determined without testwork, using mine water (or comparable proxy) under the conditions experienced at the mine. Pebble should have conducted this work long ago.

The disposal of WTP sludges in the Pyritic TSF has been proposed as a safe disposal option. However, there is no testwork to demonstrate that these sludges will remain stable and that metals will not be remobilized. I am especially concerned that the transfer of the Pyritic TSF solids into the pit lake at closure will mobilize metals. Metal remobilization in this process will increase the contaminant load reporting the WTP #3 from the pit lake and may result in an under-designed, under-performing treatment plant.

8 Conclusions

The proposed Pebble Mine is located at the headwaters of Bristol Bay, which supports a world class salmon fishery. Additionally, there are numerous wetlands that support large bird populations downstream from the mine. The sensitivity of these ecosystems requires that the mine treats its effluents to a very high quality. There is virtually no tolerance for deviation from stringent water quality criteria, since there is little dilution to decrease contaminant concentrations. This presents a great challenge to the Pebble Limited Partnership (PLP). **My assessment of their proposed water treatment scheme is that they fail to meet these standards.**

Each of the three water treatment plants (WTP) proposed in the FEIS are large, complex, and rely on some unproven technologies. This alone makes their performance uncertain, a risk that is compounded by the fact that their design is not supported by testwork, scientific and technical literature, or case studies. Considering the large number of contaminants that must be removed and the exceptionally high removal rates predicted in the FEIS, I disagree with its conclusion that the water treatment scheme will mitigate risks to the environment by producing high quality water. On the contrary, this design to treat challenging water is risky, it does not represent industry standards and its performance is premised on wildly optimistic assumptions. My own analysis indicates that it will produce non-compliant water for selenium within the life of the mine. Given the sensitivity of the receiving environment, this is an unacceptable risk.

The design for the proposed WTPs is essentially unsubstantiated by testwork, scientific and technical literature, or case studies. This is an unacceptable standard in any of the jurisdictions where I have worked professionally and it should never be acceptable in an advanced country like the USA.

The FEIS states that compliant water treatment will be achieved by using "*processes commonly used in the mining industry around the world*". This statement is demonstrably false. The treatment process for selenium removal is unproven and is not used anywhere in the mining industry. In fact, the biological treatment process originally proposed in the DEIS, the current industry standard, has been substituted with an unproven process that has not been used to remove selenium at mine sites. Additionally, the technology for sulfate removal can best be described as being at an 'advanced stage of development' rather than a proven technology. It still requires further research to prove that it can perform effectively and reliably under the conditions experienced at Pebble. There is no guarantee that conditions such as low water temperature will allow it to perform with the same effectiveness as the eMalahleni plant in South Africa. On that basis alone, there is doubt that the treatment plants will remove selenium and sulfate effectively. This could also be possible for other contaminants.

My analysis of the previous DEIS identified several problems that needed resolution (Sobolewski, 2019). Only two of these issues have been remedied. The design has been made more conservative by adopting 90^{th} percentile values as a design basis and by adding redundant treatment units. Additionally, a heat exchange system has been added to conserve heat within the system and to lower effluent temperatures. Several other problems have been left in place or made worse, casting doubt about the effectiveness of the proposed treatment system.

A significant design change from the DEIS proposal is the elimination of a biological treatment unit for selenium removal and its replacement with a two-stage chemical precipitation process. **This change cannot possibly be justified on any grounds.** The co-precipitation of selenium with iron is a well-established process. It is described incorrectly (HDR, 2019) as requiring an oxidative step, when in fact it requires a reductive step. The process has been reported to produce effluent containing selenium concentrations of 0.012-0.022 mg/L (Alberta Environment, 2005), which exceeds state standards. The follow up process, the chemical precipitation of dissolved selenium into a selenium sulfide has never been implemented at any operating mine in the world. This proposed chemical precipitation process is not credible. **PLP needs to explain why it decided to substitute a process which is known to be effective (biological treatment) for another that is unproven and inapplicable at operating mines.** Their credibility is even more questionable when they predict very low effluent selenium concentrations, when there is no testwork, no literature support and no comparable treatment system to support their claim.

I evaluated the likely fate of selenium in the water management circuit during mine operation. In this evaluation, I used defensible assumptions (presented in my analysis), as well as the Water Quality model developed by Knight Piésold, to assess the build up of salts in the Main WMP. I concluded that selenium concentrations will gradually increase in the closed water management circuit (WTP #1/#2 Brine → Pyritic

TSF → Main WMP → WTP #2 Brine) until they exceed 6 mg/L by Year 6 of operation. **At that time, selenium concentrations in the discharge of WTP #2 will exceed the Alaska state limit of 0.005 mg/L, impacting downstream environments, especially shore and waterbirds foraging and reproducing in wetlands below the mine.** These impacts will be the direct result of the decision by PLP to substitute the biological treatment system from the chemical process proposed in the FEIS.

The effluent concentrations for metals from the RO units from WTP #2 during mine operation are predicted to be exceedingly low, resulting from extremely high removal rates (Table 2). These claims are not substantiated by any testwork, scientific and technical literature or case studies. Although one case study shows comparable removal rates for a few analytes, the comparison is not applicable because of differences in starting concentrations (Table 4). Other examples show that reverse osmosis never attains the very low contaminant concentrations predicted in the FEIS. I conclude that the predicted effluent water quality is overly optimistic. Additionally, the gradual increasing concentrations of salts during mine operation (Knight Piésold, 2019) will impair treatment efficiency for the RO units. **I conclude that Pebble is proposing a water treatment system with an unrealistic treatment performance and unattainable effluent concentrations for regulated contaminants.**

This problem of salt buildup could be remedied by including a salt removal step, for example by installing an evaporator/crystallizer unit in all the WTPs. Such a unit has only been proposed for WTP #3 during Phase 1 of closure. An evaporator/crystallizer unit should have been included in the design of the other WTPs to prevent the build up of salts during operation, though it would greatly increase its capital and operating cost.

The multi-pass RO system proposed by Pebble has very few precedents at other operating mines. One of them is the eMalahleni water treatment plant. The latter system was designed to treat acid mine drainage and maximize water recovery, while producing potable water. A review of the eMalahleni treatment system states that it took 15 years to develop from concept to startup of the full-scale plant. Significantly, the development process was supported by Anglo American, a company with far greater financial and technical staff resources than Northern Dynasty. Additionally, the plant operates in South Africa, where sulfate removal from warm water is easier than in the cold water at Pebble. It is likely that developing the proposed sulfate removal process at Pebble will be more challenging and will tax the resources of Northern Dynasty Minerals. It is unacceptable to propose in a FEIS such a complex, technically-challenging treatment system without showing how the company will be able to bring it into full operation when it is needed.

In general, the R&D effort necessary to develop the treatment plants proposed in the FEIS will take several years and is beyond the capabilities of Northern Dynasty Minerals. There is a significant risk that they will not be ready to operate by the time they are required for mine operation or that they will not perform as effectively as predicted in the FEIS. The mine should not be permitted until Northern Dynasty Minerals demonstrates convincingly how it will support this development process.

RFI 021e asked for an explanation of the anticipated buildup of salts and selenium in the water management circuit. HDR, the engineering firm that designed the proposed treatment systems, responded to the question of selenium buildup incorrectly because they assumed that sulfide precipitation would remove selenium completely, an unsubstantiated assumption. I demonstrated that selenium concentrations in the Pyritic TSF and Main WMP would increase to ~6 mg/L within 6 years, resulting in the production of non-compliant effluents. Additionally, I indicated that the buildup of soluble salts will impair the treatment performance of RO units in WTP #2. **HDR's lackadaisical response to RFI 021e regarding the impacts of increasing salts reflects a poor understanding of membrane filtration systems.** This decreases considerably my confidence in their overall system design, especially since it is largely unsubstantiated by testwork, literature or case studies.

Several risks were identified in my assessment of the FEIS, including:

- Risk of ineffective performance due to system complexity and scale
- Risk of decreased removal efficiencies/RO effectiveness at increasing salt concentrations
- Risk from unconventional process for selenium removal
- Risk from unconventional process for sulfate removal
- Risk from insufficient resources for R&D
- Risk of failed treatment performance from unreliability and costs of treatment in perpetuity

In my opinion, the greatest risk to this project is the problem of long-term treatment at Pebble. Accepting Pebble's proposition that it can treat water in perpetuity assumes that the company will become wildly successful and able to cover the $1-4 billion necessary to operate and maintain their proposed treatment systems for 200-10,000 years. I have heard often similar claims in my 30 years of experience with the mining industry, but have rarely seen them substantiated. Northern Dynasty's claims beg disbelief and should be viewed with deep skepticism.

In conclusion, the water treatment system presented in the FEIS is complex and unproven and presents a high risk of causing impacts to the sensitive ecosystems downstream from the proposed mine. It should be flatly rejected.

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